Observation of Fast Particles Modes in Tore-Supra

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Abstract: Energetic particles driven modes are a concern for burning plasmas. On Tore-Supra, fast ions and electrons are generated by the RF heating systems. Fast particles driven modes are detected up to 200 kHz with ECE and reflectometry diagnostics. In ICRH plasmas, modes are observed in the acoustic frequency range, 40-70 kHz. The observed frequency agrees with the frequency predicted for both Geodesic Acoustic Modes (GAMs) and Beta Alfvén Eigenmodes BAEs, but their structure and their excitation by fast ions advocate for an identification as BAEs. The excitation threshold resulting from a balance between the fast ion drive and Landau damping by thermal ions has been quantitatively calculated. Experimental analysis displays the existence of an excitation threshold depending on various parameters such as the ICRH power, the minority fraction and the density, in agreement with the theoretical prediction.
In LHCD plasmas, electron fishbones have been detected below 20 kHz. Periodical jumps of the fishbone frequency are observed. Analysis of the mode structure show these modes are located on the q=1 surface and that the shift of frequency is linked to spontaneous transition between modes with different wave number. Moreover each jump is observed to be associated to a redistribution of the fast electrons that are resonant with these modes.

1. Introduction

The physics of energetic particles driven modes is major issue for burning plasmas. Fast particles losses may reduce the plasma self-heating or damage first wall components. Because of the fusion-driven α particles, fast ion driven modes have deserved much attention [1]. Destabilized by Ion Cyclotron Resonant Heating (ICRH) or Neutral Beam Injection (NBI) toroidal Alfvén eigenmodes (TAE) and Alfvén cascades have been extensively studied, whereas Beta Alfvén eigenmodes Alfvén modes (BAE) in the acoustic frequency range have been less studied both theoretically and experimentally [2, 3].
Less critical for reactor integrity, fast electrons redistribution may degrade the current drive efficiency and may prevent access to high performance steady state regimes. For current profile control and steady state operation both electron cyclotron current drive (ECCD) and Lower Hybrid Current Dive (LHCD) will be use in ITER. Evidence of fast electron driven modes were first recorded in DIII-D and Compass-D [4, 5] with ECCD and LHCD.
On Tore-Supra, the combined use of LHCD and ICRH systems at significant power allows fine-tuning of the q-profile and fast ions populations. High sensitivity diagnostics like fluctuations reflectometry [6] or fast and correlation ECE [7] are able to detect and localize MHD modes. In this paper we report recent results obtained on BAE and electron driven fishbones. The first part of the paper is dedicated to BAE modes. Coherent modes with a macro-scale localized structure have been observed repeatedly in the acoustic frequency range with minority heating ICRH power. Those observations have been reported with reflectometry [8] and Electron Cyclotron Emission (ECE) correlation [9]. Both their structure and the characteristics of their excitation, which appear to be intrinsically linked to the fast particle population, advocate for an identification of those modes as Beta Alfvén Eigenmodes (BAEs) [3, 10]. With this identification in mind, a careful analysis of their conditions of excitation has been carried out experimentally, displaying the existence of an excitation threshold depending on various parameters such as the ICRH power, the minority fraction, the density, and the B-field. We present this dependence as produced by our experimental investigation and we compare it with theoretical expectations. Some observations of the mode particular time evolution during a sawtooth period are also reported.

The second part deals with electron fishbones. Electron fishbones have been observed in LHCD plasmas [11, 12] in Tore-Supra. We report the observation of periodical jumps of the fishbone frequency. This novel feature is explored with measurement of the mode structure and link to the fast electron distribution using fast electron hard x-ray diagnostic. The article ends with a conclusion.

2. Beta Alfvén Eigenmodes

2.1. Description of the modes observed in the acoustic frequency range

Modes observed on Tore-Supra in the acoustic frequency range are typically observed in ICRH plasmas for toroidal field B = 2.8 to 3.8 T, a central density n = 4 to 5.5 10^{19} m^{-3}, an H minority fraction of 3% to 9% and an input of ICRH power which could be as low as 1.5 MW depending on the above parameters. They are observed sometimes in combination with TAEs, sometimes not, with a typical characteristic frequency lower than half the TAE frequency between 40 kHz and 70 kHz, and a centrally localized radial structure (typically picked inside the q = 1 surface) of rough extension going from 1 to 10cm. Unfortunately, no access to their toroidal and poloidal mode numbers is provided by magnetic coil diagnostics in Tore-Supra at those relatively large frequencies. A typical observation of those modes by the reflectometer is given in Figure 3.

In the acoustic frequency range, possible candidates for the identification of those modes belong to the Geodesic Acoustic Mode (GAM) [13, 14, 15] and BAE [2, 16] families, which are both a direct result of compressibility effects due to geodesic curvature, but differ by their mode number (n = 0 for GAMs and finite n,m for BAEs). To the lower order, the frequency of those modes is degenerate and usually approximated by the formula [16, 14]

$$\omega_0 = \frac{1}{R}\sqrt{\frac{T_i}{m_i}\left(\frac{7}{2}+2\frac{T_e}{T_i}\right)}$$

where R is the major radius, m_i the main ion mass, T_i (Te) the ion (electron) temperature.

This expression is confronted with the experiments, based on experimental measurements of Te and the reasonable assumption that $T_i \sim Te$. Figure 1 shows a rather good agreement for most experimental points within an error of 10% (representing a 30% incertitude on T_i/T_e). More precisely, the experimental data display an approximate linear scaling with ω_0. As was also observed in different machines for modes identified as BAEs [17], most experimental points are below ω_0, which may correct by the introduction of terms like diamagnetic effects, Finite Larmor Radius and Finite Orbit Width effects if the observed modes are BAEs [18]. Hence the observed frequencies appear to be consistent the GAM/BAE family.

Next, several clues call for an identification of those modes as BAEs, rather than GAMs. First of all, as was argued in Ref. [19], the GAM poloidal symmetry tends to minimize the possibility of the observations of density fluctuations in the equatorial plane where measurements of Tore-Supra reflectometer are performed. Secondly, considering a standard q-profile (pure ICRH discharges are considered) and a decreasing temperature profile, the conditions required for the existence of a GAM with a global structure [14] are not met. Finally, the clear link between the mode onset and the ICRH power suggests their excitation by the population of hot ions. As explained in Ref. [19], the excitation of an *n=0* modes is highly constrained and requires in particular an inversion of the energy gradient of the hot particle population, which our preliminary PION [20] simulations did not reproduce.

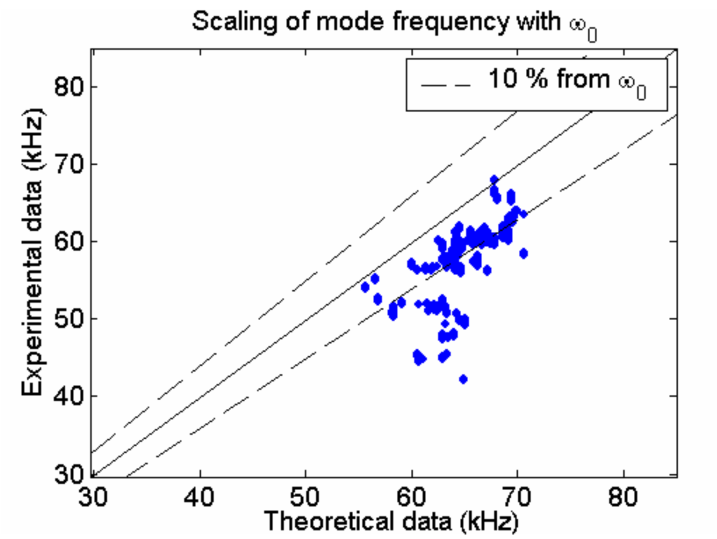

Figure 1: Comparison of the mode frequency measured with reflectometry and the traditional GAM/BAE formula given by ω_0

2.2. Parametric analysis of the mode excitation threshold

Theoretical approach

BAEs are known to be affected by Landau damping. Hence, some energy is required for their excitation and this energy may come from the hot particle population. Following ref. [19], the power transfer from the particles to the mode is given by the formula $P=2\omega\,\mathrm{Im}(\mathcal{L})$, where $\mathcal{L}$ is the electromagnetic Lagrangian. If continuum damping is neglected, the only component of the Lagrangian, which comes into P, is the resonant interaction of the different particle species with the mode. The resonant part of the Lagrangian can be calculated when the mode amplitude is small (linear regime) [19].
The main resonant processes consistent with the BAE frequency and the characteristics of Tore-Supra hot ion population are the Landau damping by bulk ions and the excitation by fast trapped ions.
The condition for linear excitation $P>0$ or $\mathrm{Im}(\mathcal{L}_{res,h}) + \mathrm{Im}(\mathcal{L}_{res,bulk}) >0$ can be put in the form

$$\frac{n_h E_{eff}}{n_i T_i}\frac{R}{L_{ph}} > A(q)B\left(\frac{E_{eff}}{T_h}\right)$$

where L_{ph} is a typical radial gradient length of the hot particle distribution. $A(.)$ and $B(.)$ are functions of the mode shape only, assumed to be constant. The E_{eff} the precession resonant energy, the hot ion temperature T_h and density n_h are considered in this expression as global characteristic quantities of the particle populations whereas q should rather be taken at the mode location.
The function B(.) defined here and proportional to $x \rightarrow 1/(x^{-3/2}\exp(-x^2))$ tends to higher the threshold for the hot ion temperature and the resonant energy needed to excite the mode are apart.

Comparison of the expected threshold with the experiments

We now link the quantities appearing in this threshold with global plasma parameters. Assuming the shape and the characteristic numbers of the mode as well as R to be constant, and $T_i=T_e$, the following scaling laws are found : $E_{eff} \propto B\sqrt{T_e}$,

$n_h T_h \propto P_{ICRH}/\nu_{ei} \propto P_{ICRH}\, T_e^{3/2}/n_e$, where ν_{ei} is the electron-ion collision frequency. Finally the threshold condition takes the form

$$\frac{n_h}{n_e}\frac{B}{\sqrt{T_e}} > c_1 B\left(c_2 \frac{n_e}{n_h}\frac{P_{ICRH}}{n_e^{\,2}}\frac{T_e}{B}\right)$$

where c_1 and c_2 are constants. The minority fraction n_h/n_e, T_e, n_e are experimentally measured. As it appears in this expression, the temperature, the B-field, the minority fraction and the ICRH power do play a role in the mode excitation.

To verify this role, we made a scan of those parameters for a fixed magnetic configuration at $B=3.8T$, two densities n_e=5 and 4.5 10^{19} m^{-3}, hydrogen injections allowing a scan of the minority fraction ranging from 2.5% to 10%, and repeated increases ICRH power. The results of this investigation are presented in Figure 2.

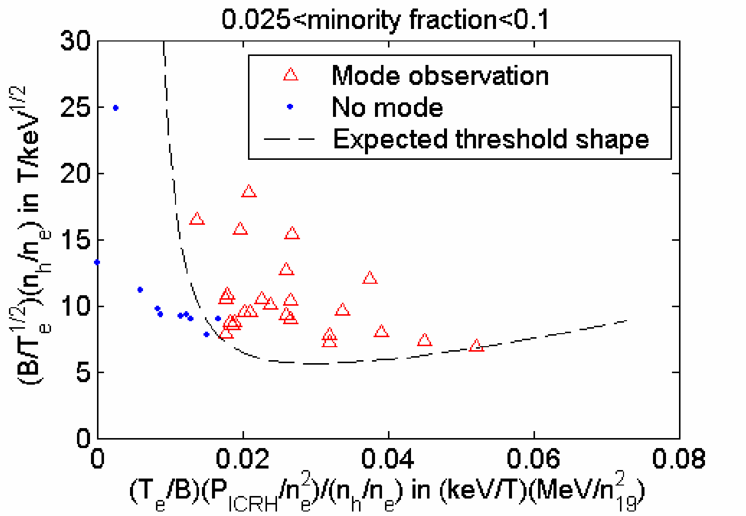

Figure 2 :Stability diagram of BAE modes on Tore Supra

2.3 Evolution of the mode frequency and magnitude during a sawtooth period

This series of experiments led us to some interesting observations of the mode frequency evolution during a sawtooth period. As can be seen in figure 3, the mode frequency tends to increase drastically at the end of the sawtooth period: from 50 kHz at t~9.6 the frequency increases to 100 kHz just before the sawtooth crash. Just after the crash, the mode frequency is back to 50 kHz and slowly decreases up to t=9.65 when the amplitude becomes too low to be seen on the spectrogram. Several explanations may be proposed, such as a possible role of the shape of the hot ions distribution. But at the moment, further investigation is needed.

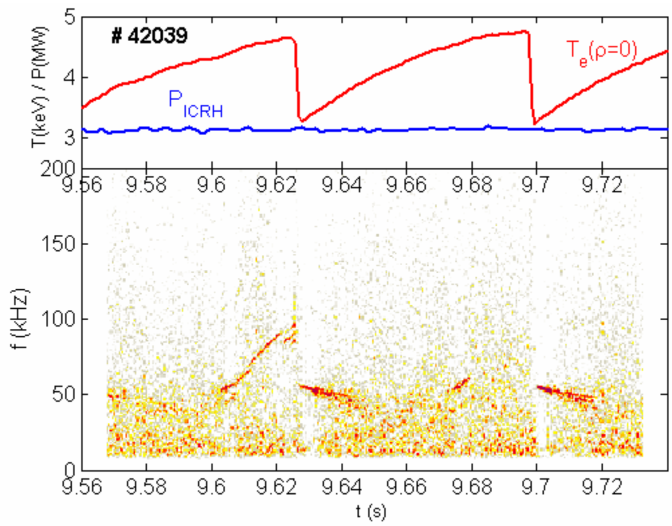

Figure 3: Spectrogram of the phase of the reflectometry signal at ρ~0 during sawtooth periods. The central temperature (red) is shown on the top. The ICRH power (blue) is constant.

3. Electron fishbones

3.1 Observation of fishbone frequency jumps

In LHCD discharges, coherent modes at frequencies between 3 to 20 kHz are observed with ECE and fluctuation reflectometry diagnostics. By varying the LH power during a rather a long discharges (B=3.1T, Ip=0.6 MA, n_e=2.5 10^{19} m^{-3}, Vloop~0.15 V) we have observed evolution of the mode frequency.

- At low power, the mode frequency range is above 8-10 kHz. It is characterized by frequency jumps and an oscillation of the electron temperature (ΔTe/Te ~ 1%) (see Figure 4 a). This mode is excited by fast particles since the mode disappear when the LH power drops. The mode frequency is consistent with precession electron fishbone [21] characterized by the frequency $\omega_p = \dfrac{nEq}{rR_0B}$ where n is the toroidal mode number, E the energy of the resonant particles, q is the safety factor associated to the resonant surface located by the small radius r, R_0 is the major radius [22].
- Above a power threshold (1.3 MW in this discharge), another mode is observed at much lower frequency, 2-4 kHz. The frequency is steady and the central oscillation disappears. When increasing LH power, we observe a frequency rise. This mode is linked to diamagnetic rotation since the mode frequency follows the thermal electron temperature and not the suprathermal energy.

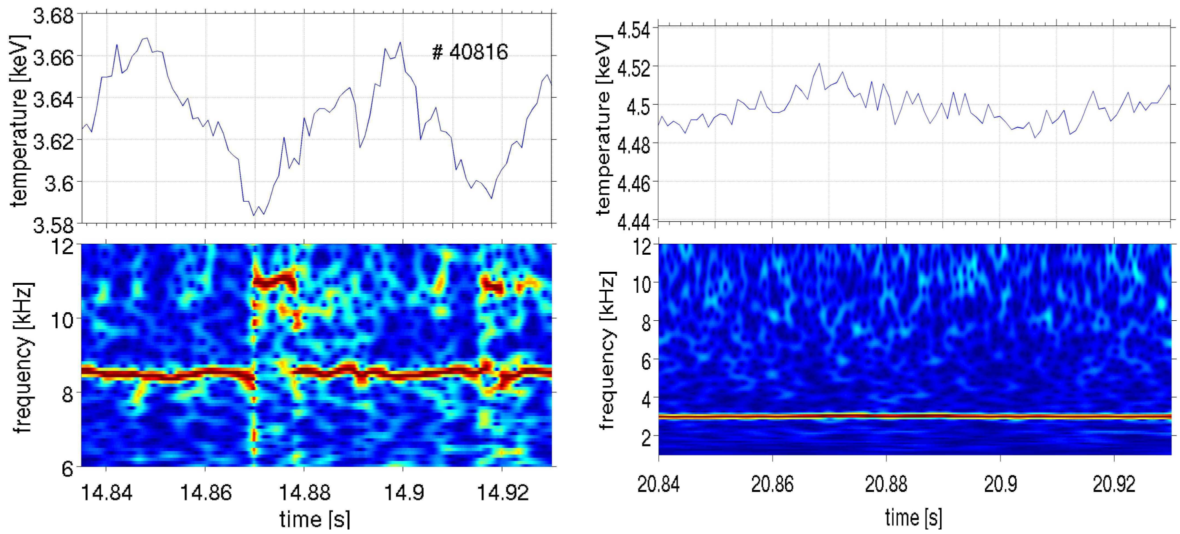

Figure 4: a): Observation of frequency jumps (spectrogram of ECE channel at r/a=0.2) with P_{LH}=1 MW. The central ECE channel is shown in the upper panel. b) Same shot with P_{LH}=1.3 MW. The mode frequency is lower and constant and the central temperature oscillation disappears.

3.2 Fishbone structure

Using fast-ECE diagnostic (up to 120 ms acquired with 83 kHz of sampling rate for all the 32-ECE channels) the modes shown on figure 5a) have been analyzed. These instabilities are localized around ρ=0.16 ± 0.03 as shown by radial mode structures, figure 5b, c and d. From CRONOS simulation taking into account the Hard X ray measurements to constrain the LH absorption [23], the q=1 surface is located at ρ~0.2.

Even if no direct evaluation of mode numbers is available, indirect evidence of changes of the poloidal mode number, from odd to even value and vice versa, can be obtained looking at the axial symmetry of the amplitude radial profile multiplied by the phase of each channels.

Unlike other modes around 11 kHz and 9 kHz, the lower detected frequency results to have an even m-number. Being at the resonant surface q = 1, one has *m =n*.

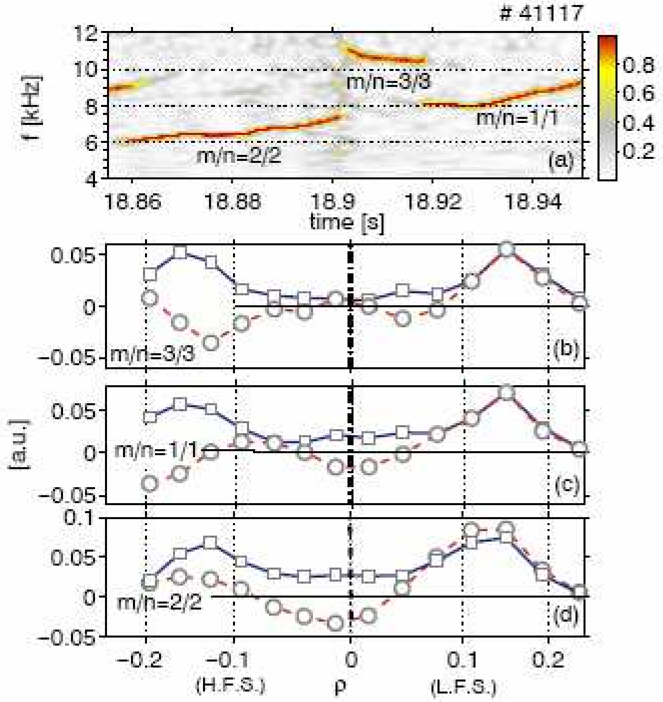

figure 5: (a), Spectrogram of fast-ECE signal corresponding to ρ = 0.16 ± 0.03 .(b), (c), and (d) Average profiles of temperature fluctuation amplitudes, $A(\rho)$, (squares and blu solid lines) and parity $A(\rho)cos(\Phi_\rho)$ (circles and dashed red line). Φ_ρ is the signal phase (Φ_ρ=0 at ρ =0.16).

3.3 Redistribution of fast electron

Fast-ECE acquisitions have been recorded for the mode shown figure 4a). In one particular complete period, these jumps have been isolated. The modes at 8.5 kHz and 11 kHz are localized around the q = 1 surface as confirmed respectively by ECE radial amplitude profiles and by the CRONOS code, while their *m* numbers are both odd. Hard-X ray observations in three different energy bands, respectively 60-80 keV, 40-60 keV, and 20-40 keV are shown in Figure 6b, c and d. These figures are the result of a topographic inversion of line-integrated measurements over 21 horizontal chords and 38 vertical lines of sight [24].
While the intermediate channel presents little change over time, drastic change of the 20-40 keV and 60 -80 keV occurs between t=14.872s (mode at 11 kHz) and t=14906s (mode at 8.5 kHz). When the mode at 9 kHz develops, the 60-80 kHz electron distribution profile is hollow (see Figure7)) meaning 60 and 80 keV suprathermal electrons are lost in the center. On the contrary, the 20-40 kHz electron distribution profile is hollow when the 11 kHz appears. This interval still belongs to the usual range of fast electrons created by the LH in Tore-Supra.
While the modes frequency changes from 9 to 11 kHz, the electron energy band changes from 60-80 keV to 20-40 keV, decreasing by a factor 3 and the modes conserves its odd parity. This evolution is compatible with a change of the mode number from *m=n=1* to *m=n=3*. More precisely, assuming *m=n=1*, the electron fishbone frequency given by $\omega_p = \frac{nEq}{rRB}$ lies between 8 kHz for 60 keV electron to 10.7 kHz for 80 keV. For 20-40 keV electron and *m=n=3*, the electron fishbones frequency ranges between 8 and 16 kHz.

We can propose the following scenario for the frequency evolution of the electron fishbone jumps [22]. When the m=n=3 fishbone mode develops, the radial profile of the 60-80 keV electron that are not affected by the mode is flat in the center. When the m=n=1 mode is excited and the m=n=3 mode disappears, 60-70 keV electrons are lost in the center and the profile becomes hollow (blue area). Moreover, an increase of the signal is observed outside $\rho=0.2$, a clear sign of fast electron redistribution. The time evolution of the 20-40 keV electron distribution is inverted. Remarkably, the intersection of the two profiles, w/o and with instability effects, is found at $\rho \approx 0.2$ where the modes are localized.
The reason for the changes of mode number and resonant energy remains to be found.

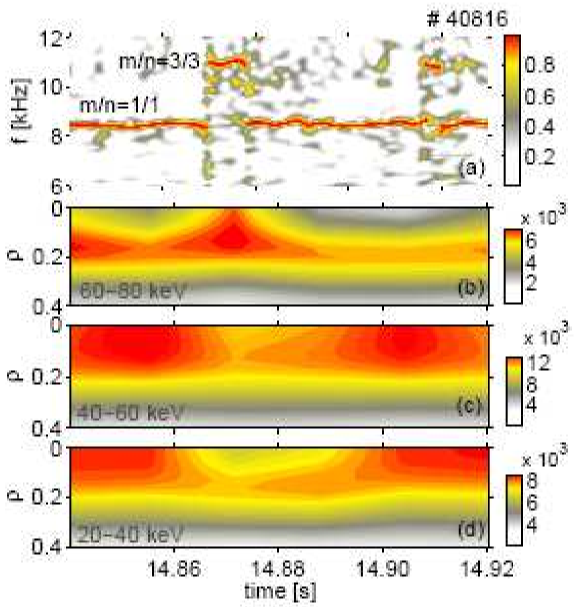

Figure 6:(a), Spectrogram obtained by fast ECE diagnostic. (b), (c), and (d) are respectively the filled contour plot of the electron photon emission in the energy bands 60-80 keV, 40-60 keV, and 20-40 keV obtained by hard X-measurement.

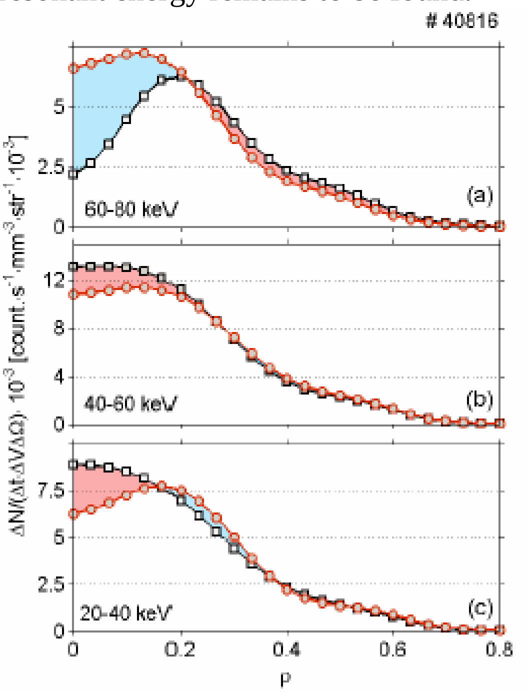

figure 7:Hard X-ray radial profiles related to Figure6b, c and d at time *t=14.872s* (red lines marked by circles) and *t=14.906s* (black line & squares). a) 60-80 keV energy band, (b) 40-60 keV and (c) in the 20-40 keV interval.

4. Conclusion

Fast ion and fast electron driven mode particles driven modes can be excited on Tore-Supra. In ICRH plasmas, Beta Alfvén Eigenmodes are repeatedly observed. The mode frequency follows the prediction for BAE/GAM. The excitation threshold depends on various parameters such as the ICRH power, the minority fraction, the density, and the B-field in agreement with theoretical calculation. We have also observed a fast increase of the BAE frequency just before a sawtooth crash. In LHCD plasmas, jumps of the electron fishbone frequency have been observed. This novel feature is linked to a modification the mode wavenumber and the energy of electrons that are resonant with the mode.
Most studies on fast particles have dealt with a unique energetic population. But in steady-state burning plasma, fast ions and electrons could interact and we could not exclude synergetic effect to destabilized MHD modes. Alfvén eigenmodes driven by fast electron

driven modes were recently observed in Alcator C-mod [25]. With its capability to launch LHCD and ICRH at significant power, such studies could be done on Tore-Supra.

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